Cosmology with Line Intensity Mapping

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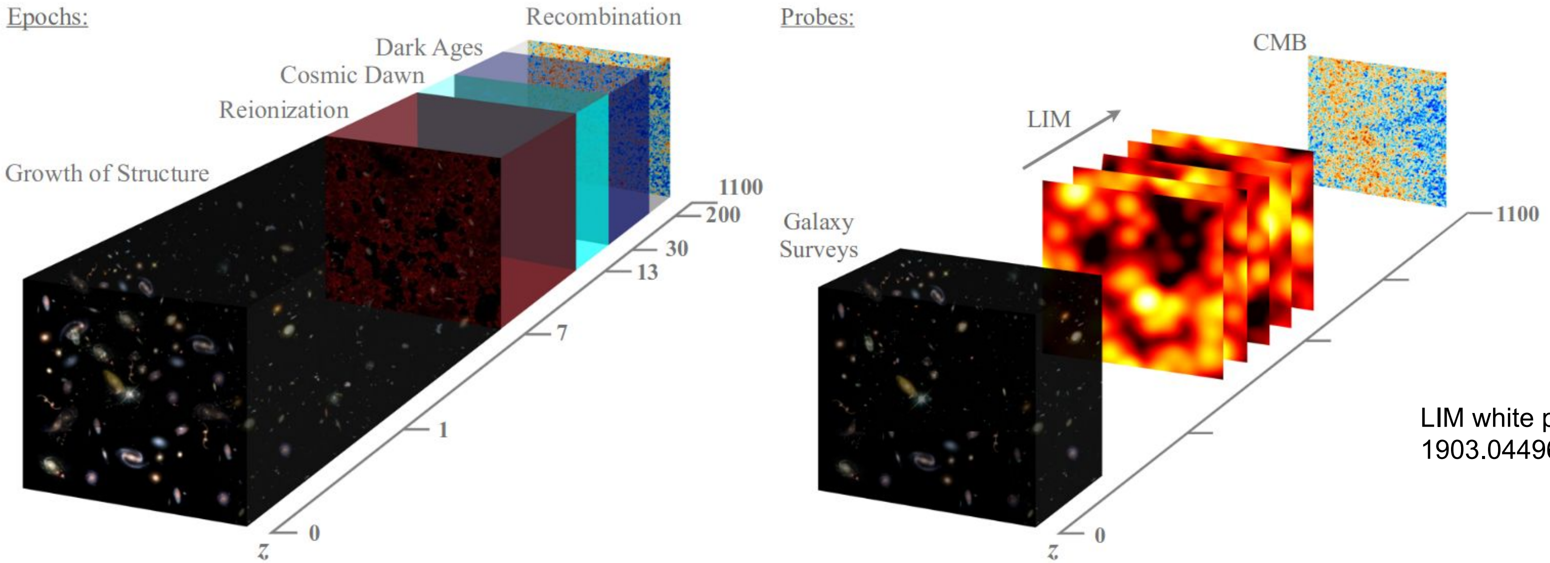
University of Chicago/Fermilab
CMB-S4 Collaboration Meeting, 2022-08-18

Line Intensity Mapping (LIM)



LIM white paper
1903.04496

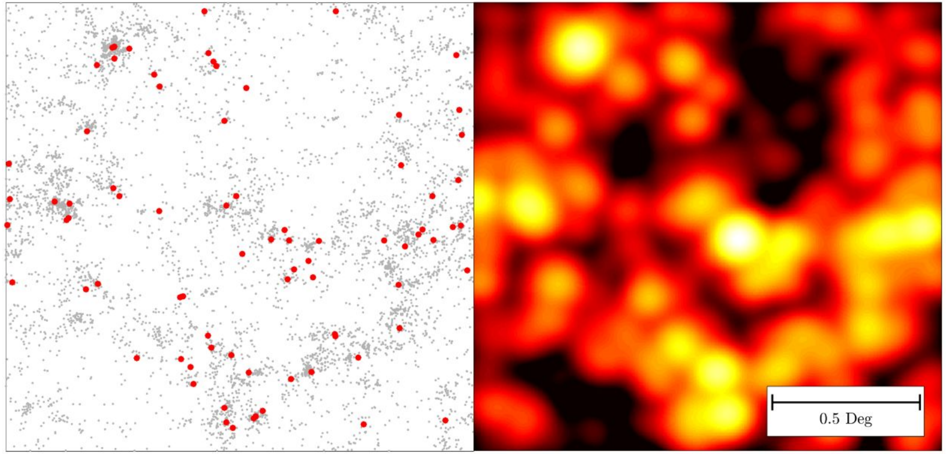
LIM uses moderate-resolution observations to detect large-scale structure in aggregate.

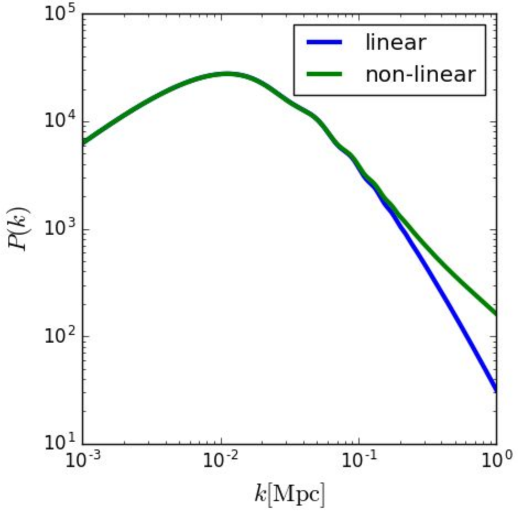
Use a spectrometer to detect fluctuations in a line emitted by LSS →maps are in 3D.

Potential for measuring LSS at much higher redshifts than traditional galaxy surveys!

Line Intensity Mapping (LIM)

LIM Status Report
1709.09066





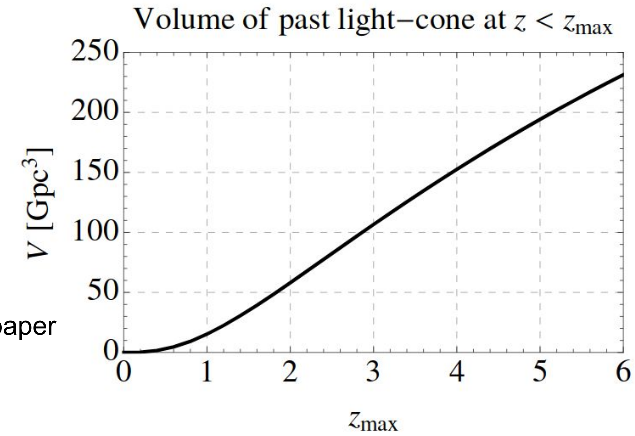
In a traditional galaxy survey you get the same SNR on all scales - but the majority of cosmological information comes from large scales.

For scales much larger than the individual galaxies, the overall signal still traces the underlying number density. LIM places the sensitivity where it's really needed.

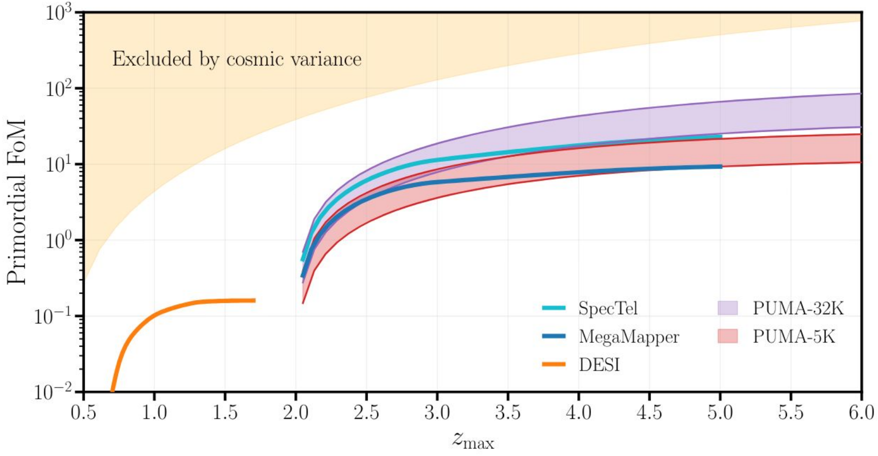
This makes LIM more efficient at high redshift where individual galaxies are hard to detect.

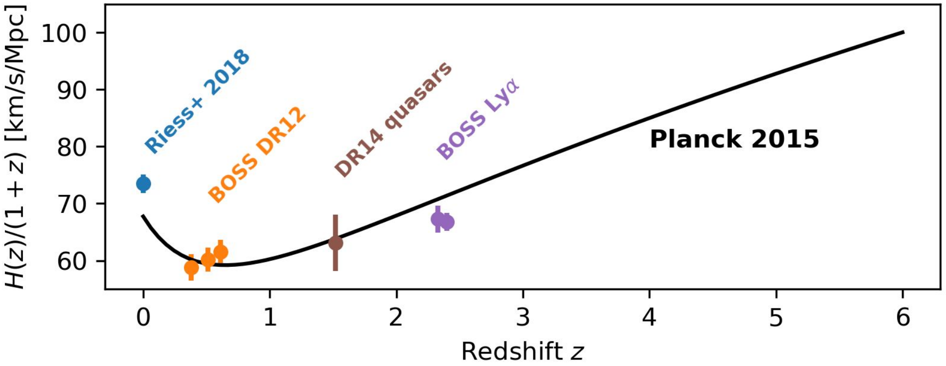
Snowmass CF4 White paper
2203.07506

Why go to higher redshift?



HI Stage 2 White paper
1810.09572





Many more modes available.

Measure LSS in different epochs - a wide redshift lever arm alleviates parameter degeneracies.

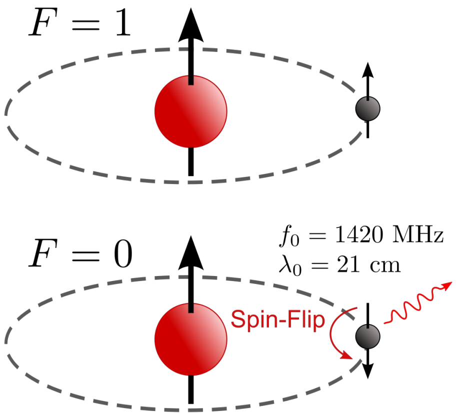
Nonlinearities are smaller at higher redshift.

LIM Cosmology Science Cases

High-redshift LSS Snowmass white paper 2203.07606
Mm-wave LIM Snowmass white paper 2203.07258

Science case	Primordial non-Gaussianity	Neutrino masses	Light relic particles	Dark energy, modified gravity
Measurement	Scale-dependent bias in power spectrum, bispectrum	Suppression of power spectrum on small scales, expansion history	Power spectrum amplitude, phase and amplitude of BAO	Power spectrum (BAO), growth of structure
Parameter	f_{NL}	M_ν	N_{eff}	w_0 , w_a
LIM advantage	Large volume, large-scale modes, bispectrum SNR is a sharp function of smallest scale	Capture redshift evolution of power spectrum, break degeneracies	Large volume, break degeneracy in CMB measurements	Wide redshift access, unique sensitivity to early dark energy

LIM targets: 21 cm



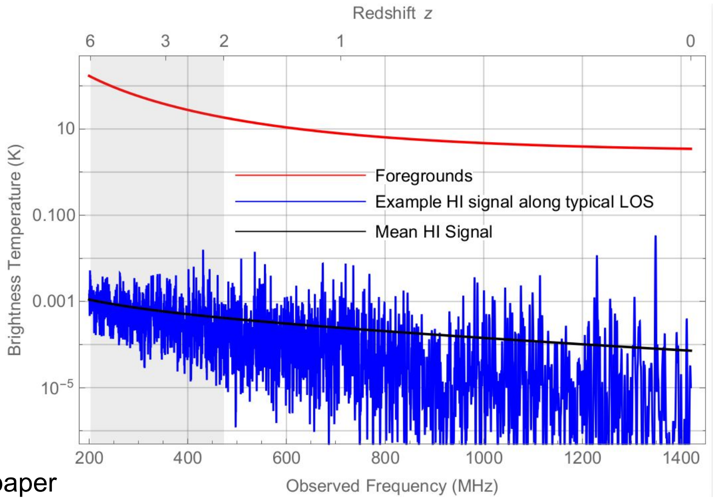
Hyperfine transition of neutral hydrogen at 1420 MHz

Advantages:

- Access to an extremely wide redshift range
  - Dark ages (20 < z < 150) - pristine primordial density field
  - Reionization (6 < z < 20) - bubbles of ionized gas in neutral IGM - lots of interesting astrophysics
  - Low redshift (z < 6) - neutral hydrogen in galaxies
- The only transition in its frequency range

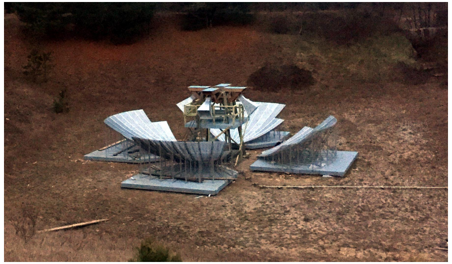
Disadvantages

- Galactic foregrounds are extremely bright
- Large arrays of physically-large antennas
  - Calibration is difficult (instrument chromaticity leaks foreground into signal)



HI Stage 2 White paper
1810.09572

21 cm Experimental Landscape

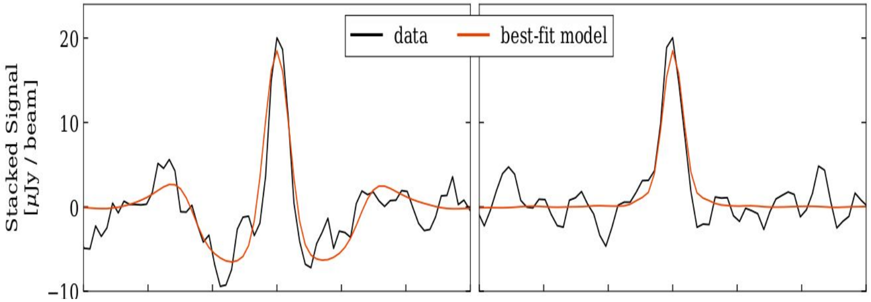


BMX pathfinder

CHIME

PUMA, CHORD

HIRAX



Many-sigma detections in cross-correlation

CHIME 2202.01242

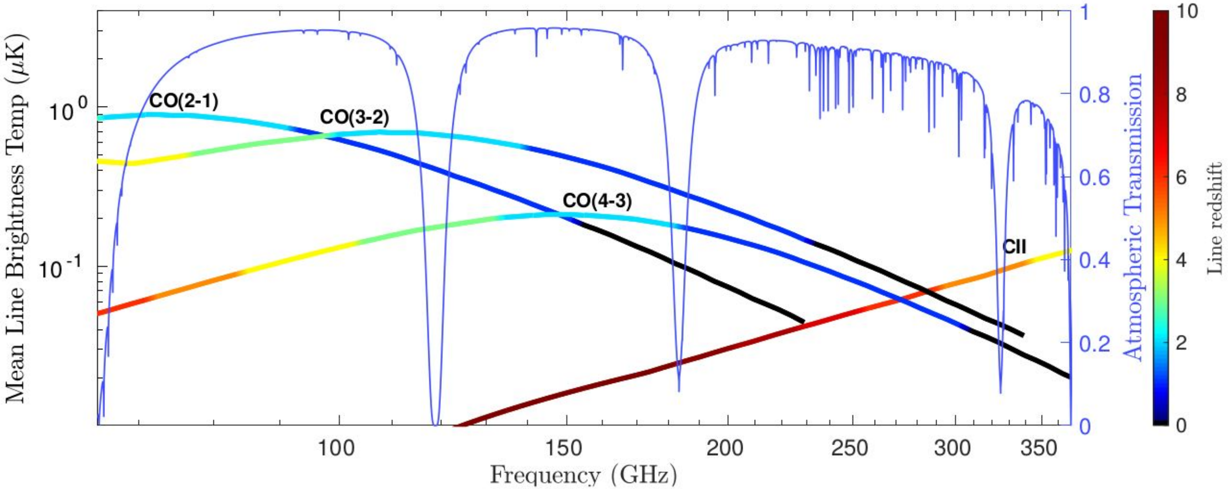
LIM Targets: Far-IR lines

Garrett Keating

Atomic and molecular species in dusty galaxies absorb stellar light and emit in the far-IR. Typical lines:

- [CII] ionized carbon, 158 um
- CO($J \rightarrow J$-1), 115J GHz

Observations from 80-300 GHz are sensitive to emission from $0 < z < 10$.



Advantages:

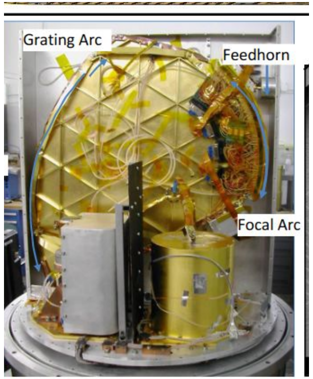
- CMB heritage - leverage experience with CMB detectors to scale up *spectroscopic* focal planes, scan and calibration strategies optimized for deep observations on large scales. Can reuse CMB facilities!
- Continuum galaxy-to-signal ratio significantly smaller than for HI

Disadvantages:

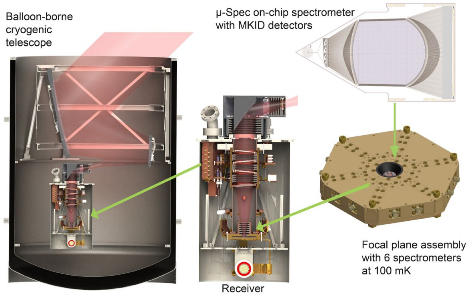
- Line confusion
- Unlikely to access beyond EoR

mm-wave LIM Experimental Landscape

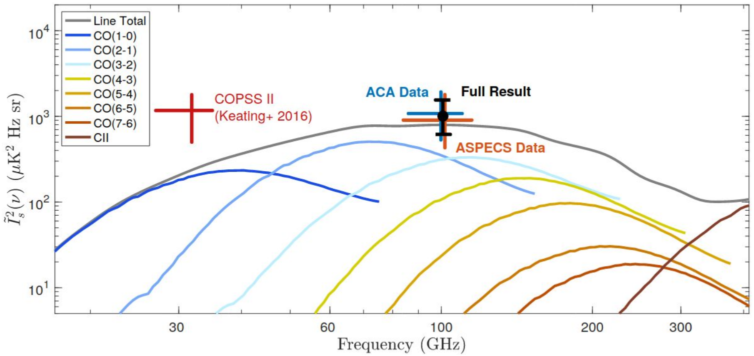
COPSS/mmIME 2008.08087

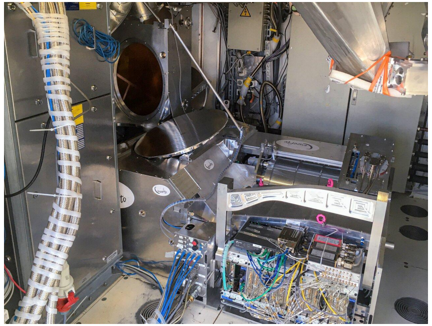


TIME

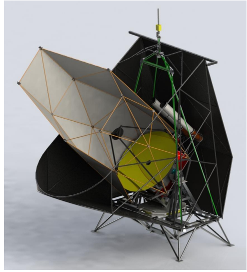


EXCLAIM

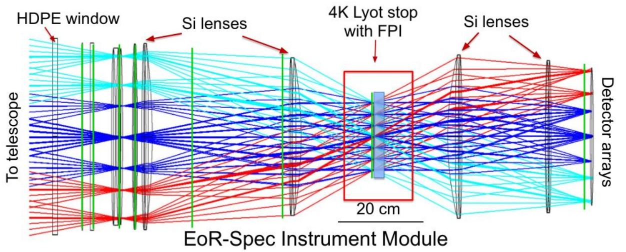




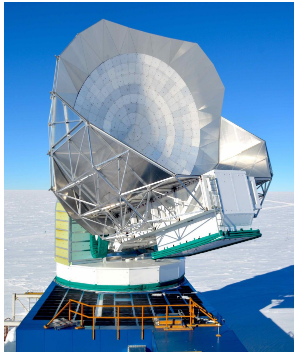
CONCERTO



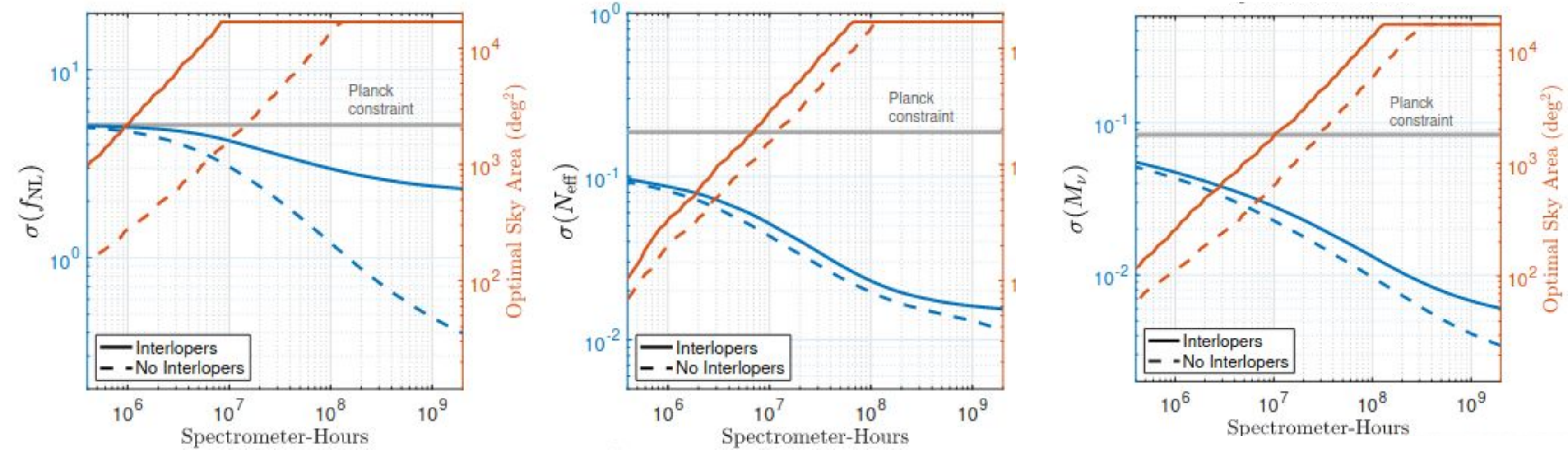
TIM

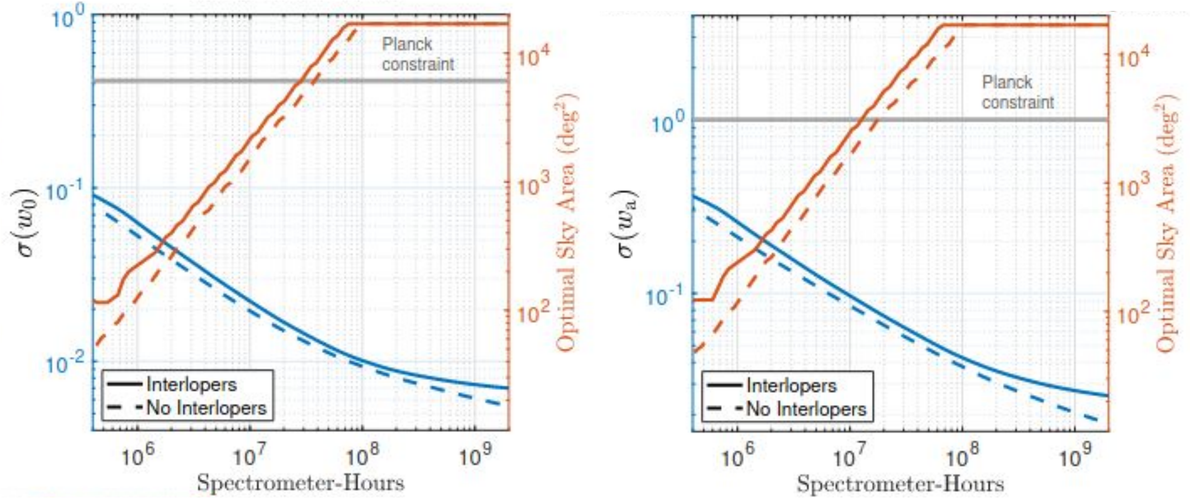


CCAT-p



SPT-SLIM





Forecasts for mm-wave LIM sensitivity to cosmological science cases parametrized by *spectrometer-hours*
80-300 GHz, R=300

LIM Snowmass white paper
2203.07258

A Staged Approach to Improving Sensitivity

Spec-hrs	Example	Time-scale	$\sigma(f_{\rm NL})$	$\sigma(M_\nu)$ (meV)	$\sigma(N_{\rm eff})$	$\sigma(w_0) \times 10^2$	$\sigma(w_{\rm a}) \times 10^2$
10^5	TIME, CCAT-p, SPT-SLIM	2022	5.1 (5.1)	61 (65)	0.1 (0.11)	13 (14)	51 (52)
10^6	TIME-EXT	2025	4.7 (5)	43 (47)	0.082 (0.087)	5.3 (6.3)	21 (26)
10^7	SPT-like 1 tube	2028	3.1 (4.2)	23 (28)	0.043 (0.051)	2 (2.2)	8.5 (9.7)
10^8	SPT-like 7 tubes	2031	1.2 (3)	9.7 (13)	0.02 (0.023)	0.93 (1)	3.8 (4.3)
10^9	CMB-S4-like 85 tubes	2037	0.48 (2.4)	4.1 (6.8)	0.013 (0.016)	0.61 (0.73)	2.1 (2.8)
Planck			5.1	83	0.187	41	100

LIM becomes competitive with galaxy surveys in the $\sim 10^7$ spectrometer-hour range

LIM Snowmass white paper
2203.07258

Technical Advances Needed for LIM Cosmology

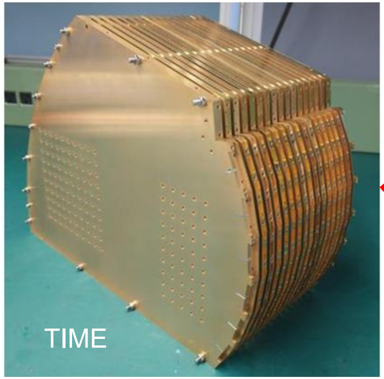
21 cm:

- Early digitization and RFI shielding
- Optimized analog radio receivers
- Beam measurements and calibration (interaction with foregrounds)

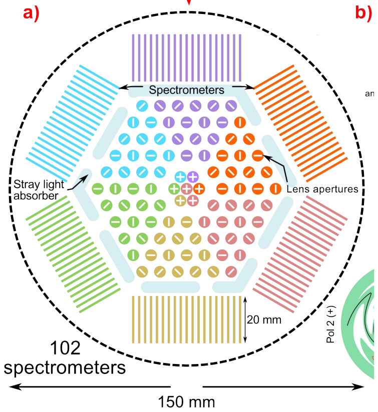
mm-wave:

- High-density spectroscopic focal planes
- High-density microwave readout
- Analysis techniques to deal with line confusion

…and everything must be validated on pathfinder experiments!



E. Shirokoff



P. Barry

Mm-wave LIM Snowmass white paper 2203.07258
21 cm LIM Snowmass white paper 2203.07864

Conclusions

LIM offers a natural path to extending the volume of LSS observations, allowing us to constrain cosmology with higher precision and at different epochs.

Pathfinder experiments are now getting first detections and demonstrating an array of instrumentation and analysis techniques.

Investment in enabling technologies, analysis, and future experiments is necessary for LIM cosmology to reach its full potential!

See various Snowmass white papers and topical reports (CF4/5/6) for more details:

- High-redshift LSS 2203.07506
- 21 cm LIM 2203.07864
- mm-wave LIM 2203.07258